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Final Report

NAG 5-1225

Analysis of Data from the HEAO-2/*Einstein* Observatory

MIT Center for Space Research

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I. Introduction

For this project we proposed to do a study of three type I supernova remnants (the remnants of the supernovae of 1572 (Tycho), 1604 (Kepler) and 1006 [called simply SN1006]). The data base we consulted was the set of high resolution X-ray spectra obtained with the Focal Plane Spectrometer (FPCS, see Canizares *et al.*, 1977, 1979) on the *Einstein* (HEAO-2) satellite. Our goal was to use a two-pronged approach to the analysis of the X-ray spectra: first, to use plasma diagnostics of the data in a model-independent way (to the extent possible), and obtain information of temperatures, ion fractions, ionization time-scales, and abundances; and second, to incorporate the data into comprehensive models to test the validity of the models and constrain the astrophysical parameters (e.g., Brinkman *et al.*, 1989; Hamilton, Sarazin, and Szymkowiak, 1986 ≡ HSS). While this project is not yet complete, we have made significant progress, which we discuss below.

II. Work done

A. Data reduction

Most of the data for the objects of interest had already been reduced (i.e., we had individual spectral scans in hand, and often had values or upper limits for line fluxes). In a few cases it was appropriate to refine the reduction technique, and this either has been done or is currently being completed.

B. Plasma diagnostics and spectral models

The technique of using line ratios to determine properties of the X-ray emitting plasma has been undergoing refinement for several years now. We have spent a great deal of time and effort in improving these methods and have applied them to a number of objects (e.g., Hwang, et al., 1992). The enclosed figure shows an example of how the ratio of line intensities for an observation of the Cas A supernova remnant was used to constrain two plasma parameters (electron temperature and ionization timescale). Similar graphs have been made for the Tycho SNR (see Moore 1990, appended). Some of our effort during this period has gone into improving the plasma diagnostic technique so as to incorporate up-to-date atomic physics parameters. We have also been examining (and applying to our data) comprehensive SNR models which predict the total X-ray spectra. In particular, Moore examined the model of Brinkman *et al.*

C. Results for Tycho

The work to date has concentrated on refining the analysis techniques (plasma diagnostics and spectral models) and an application of these techniques to the Tycho remnant (Moore 1990)). Moore's results constrained the temperature and ion times for this particular SNR. He found an ionization timescale in the range $\log \tau = 2.4$-3.3 cm^{-3} yr. His comparison with the predictions of the Brinkman *et al.* model indicate that there are some fundamental problems with the atomic physics assumptions used by Brinkman.

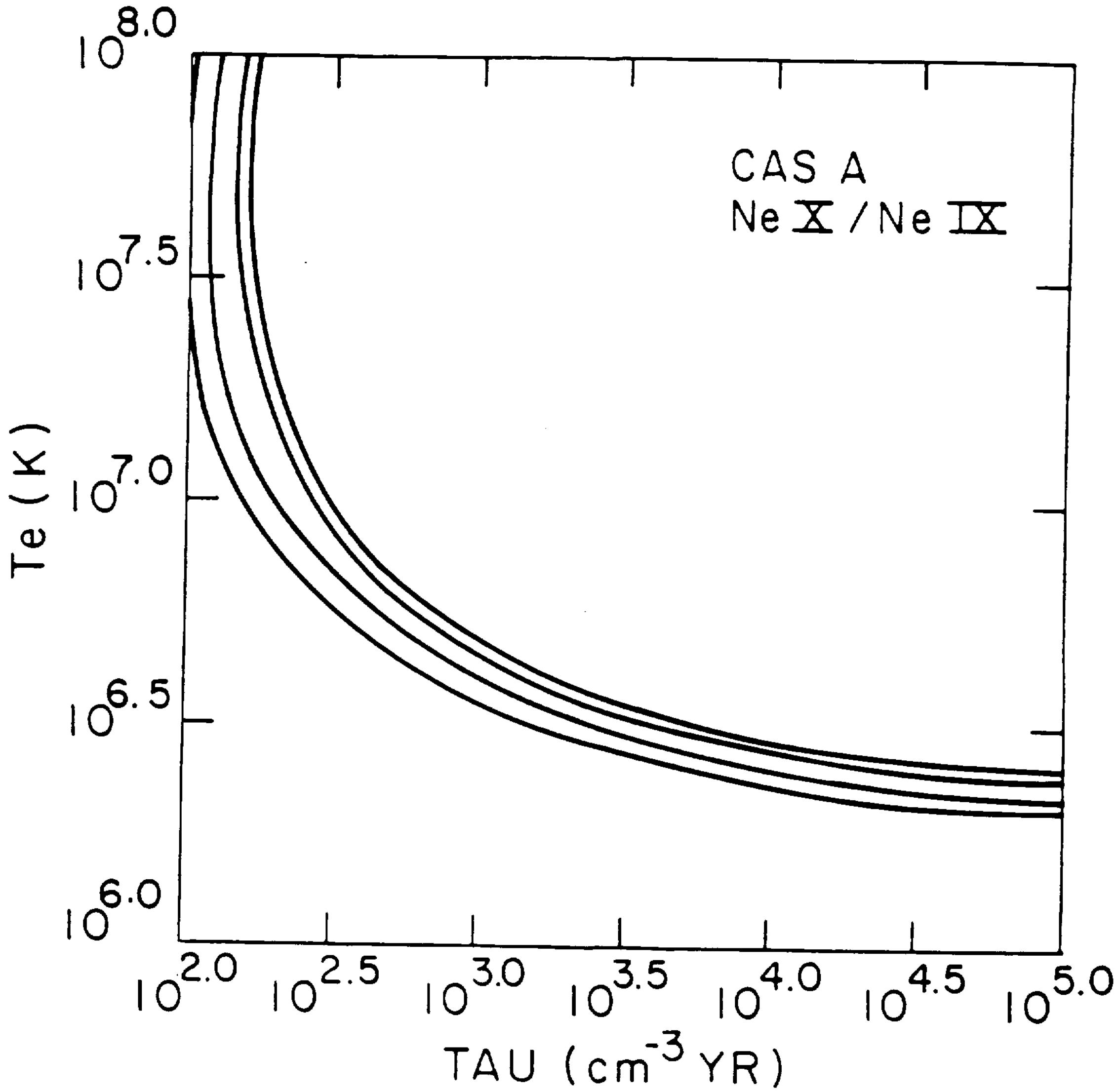
D. Future work

We have a graduate student, Una Hwang, who is continuing with Moore's analysis of Tycho, and eventually will continue with Kepler and SN1006. She has done a great deal of work to refine the plasma diagnostic technique and to expand it so as to use the emissivity and ionization balance code of John Raymond (private communication).. Our work to date has used the ionization technique of Hughes and Helfand (1985) and the radiation rates of Mewe and Gronenschild (1981) and Mewe, Gronenschild and van den Oord (1985).

A large part of the FPCS effort in recent years has been in producing an overall spectral catalog and a useful archive of the FPCS data base. The spectral catalog has been completed and will be published soon (Lum *et al.*, 1992) and Ken Lum has also worked hard to transfer the FPCS data to UNIX-based computers for more general use. Hwang and others have moved the relevant analysis software to the UNIX systems, so that faster and more reliable analysis of the FPCS data can occur. We believe that the work with the Type I SNR's will now proceed more rapidly on the UNIX system.

III. Conclusions

While we have not completed the Type I SNR project, we have laid a great deal of the ground work and done a preliminary analysis of the Tycho SNR. Hwang is now proceeding with the final work on Tycho and will then extend her analysis to Kepler and SN1006.



An illustration of how measurements of a flux ratio can constrain the allowed values of the electron temperature T_e and the ionization time τ ($=n_e \times t$). The ratio is that of the intensity of the Lyman alpha line for hydrogen-like neon, to the intensity of the n=2 to n=1 transitions for helium-like neon. The data is from an observation of the Cas A supernova remnant, made with the Focal Plane Crystal Spectroemeter on the *Einstein* Observatory. The contours are 1s and 2s, and the regions within the contour lines are those values of (T_e,τ) which give predicted flux ratios consistent with the the Cas A observations.

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Moore, C.B., "High Resolution X-ray Spectroscopic Measurements of the Tycho Supernova Remnant", MIT Bachelor's Thesis, 1990.

Appendix

"High Resoltion X-ray Spectroscopic Measurements of the Tycho Supernova Remant"
Christopher B. Moore
Bachelor's Thesis, MIT Department of Physics
June 1990

High Resolution X-Ray Spectroscopic Measurements of the Tycho Supernova Remnant

by
Christopher Bennett Moore

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High Resolution X-Ray Spectroscopic Measurements of the Tycho Supernova Remnant

by

Christopher Bennett Moore

Submitted to the Department of Physics
on May 25, 1990 in partial fulfillment of the
requirements for the Degree of
Bachelor of Science in Physics

ABSTRACT
I have compared high resolution X-ray spectroscopic observations of Tycho's supernova remnant to the predictions of a numerical model of the remnant by Brinkmann, *et al.* I find that the model fails to predict the flux ratios for several interesting line pairs and suspect that there are some fundamental problems in the atomic physics used in the model. I have also applied plasma diagnostics under the assumption that the remnant can be characterized by a single mean temperature, T, and ionization time, τ. Asssuming $\log(\tau) = 2.4\text{–}3.3$ cm^{-3} years, our observational data suggest that the electron temperature of the remnant is $\log(T) \geq 7.5$.

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1 Introduction

A supernova (SN) is a cataclysmic explosion marking the death of a star. Stars of approximately one solar mass (Type I supernovae) as well as massive stars $\gtrsim 7$ solar masses (Type II supernovae) undergo such explosive deaths. Stars of intermediate mass die by gently puffing off their outer envelopes. Type I SNae are believed to be powered by nuclear reactions (e.g. deflagration of a white-dwarf) while Type II explosions derive most of their energy from gravitational collapse of a stellar core to form a neutron star or black hole[4].

SNae typically involve the ejection of at least one solar mass of material into the surrounding interstellar medium at velocities reaching 10^4 km s^{-1}[9]. The resulting supernova remnant (SNR) is typically observable in radio, optical, and X-rays for many thousands of years. SNRs are also interesting since they provide our only direct look at stellar interiors. In order to understand what the X-ray emission of a SNR tells us about the SR that formed it, we must first understand the physical properties of the emitting plasma. One of the critical properties of a SNR plasma is the relationship between the characteristic temperatures of the ions, the electrons, and the ionization state of various elements.

Here, we examine one SNR in particular: the remnant of SN 1572, also known as Tycho's SNR since the supernova explosion was witnessed and recorded by Tycho Brahe. An X-ray image of Tycho's SNR (see Figure [1]) shows a nearly spherically symmetric shell of hot matter propagating outward with cooler ejecta in the interior.

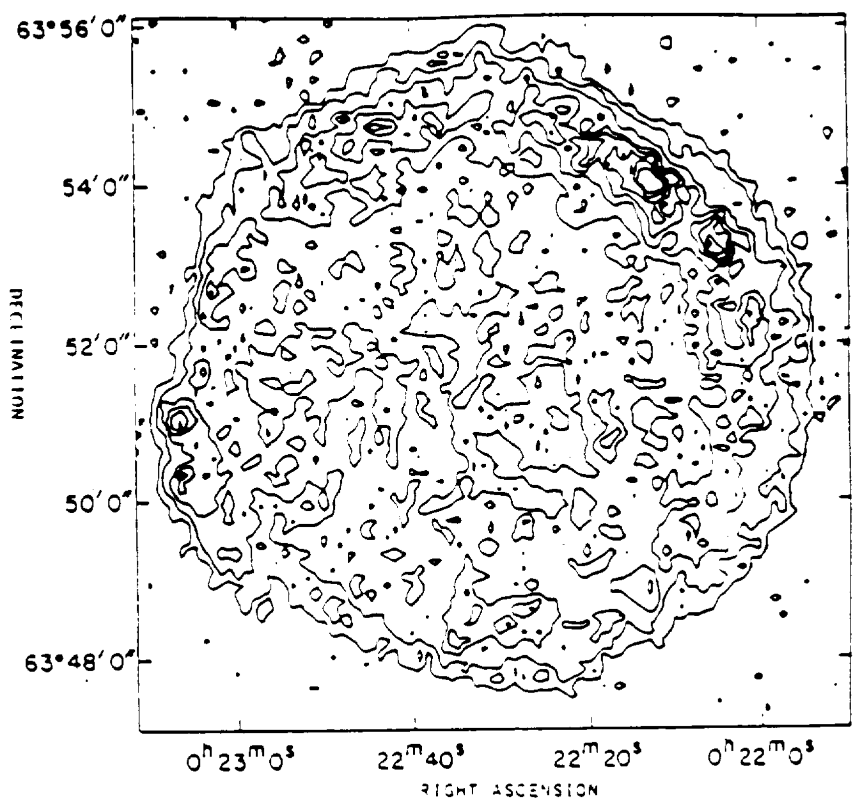

Figure 1: HRI X-Ray Map of Tycho's supernova remnant[18].

SN 1572 is believed to have been a Type I supernova; previous investigators have determined that it is ~3kpc distant, contains about four solar masses of emitting material, and is ~7pc across. Brinkmann, *et al.* have created a numerical model of the remnant expected from a Type I SN. In this paper we will examine data collected with the curved crystal Bragg spectrometer aboard the *Einstein* X-ray observatory and compare them to the predictions of the numerical model.

2 The *Einstein* X-Ray Observatory

2.1 Hardware

The *Einstein*(HEAO-2) observatory, which was launched in November of 1978, was the first satellite X-ray observatory to make use of an imaging X-ray telescope[8]. X-ray telescopes cannot focus their images with traditional mirrors and lenses because X-rays are absorbed rather than refracted by most materials and because traditional (i.e. near normal incidence) mirrors do not reflect X-rays. In the 1930's X-rays were found to reflect from smooth surfaces at very small angles of incidence. This "grazing incidence reflection" is the basis for *Einstein's* imaging telescope. It is a Wolter type I arrangement in which grazing incidence X-rays undergo two reflections: the first, off a paraboloid and the second off a confocal, coaxial hyperboloid. On axis rays are first reflected towards the common focus by the paraboloid and then reflected by the hyperboloid to its other focus.

As a result of the grazing incidence arrangement, such mirrors have a very small effective area. Since photons striking a disc in the middle of the mirror are not focused, it is possible to enlarge the effective area of a telescope without increasing its size by producing a set of nested grazing incidence mirrors. The telescope aboard *Einstein* had four such mirrors with optical diameters ranging from 33 to 56 centimeters and achieved a resolution of about two arc seconds in their operating range of ~0.2–4keV[8].

The telescope's focal plane contained four instruments that could be rotated into position on a turret. These included a high-resolution imaging detector (HRI), a broad field imaging proportional counter (IPC), a solid state spectrometer (SSS), and a focal plane crystal spectrometer (FPCS). The FPCS was a curved crystal Bragg spectrometer that achieved a resolution ($\frac{E}{\Delta E}$) as large as 1000: the highest resolution of the spectrometers aboard *Einstein*[5]. The detector for the FPCS was a seven wire imaging proportional counter with ~1 mm resolution along the dispersion direction and 1 cm (wire-to-wire) resolution in the orthogonal direction. The imaging and energy resolving capabilities of the detector are used to reduce the background rate as described below.

2.2 Data Analysis

A high resolution spectrometer like the FPCS necessarily has a very low efficiency. This results in a low count rate at the detector and makes good background reduction essential. For each detected event, we know the crystal angle, the wire in the detector on which the event was detected, and the output voltages from each end of the wire. The total charge collected by the wire gives a pulse height which is a (rough) indication of the total energy of the event. Since the detector wires have uniform resistance along their length, the electronic charge collected by an event is divided between the two ends of the wire in inverse proportion to the position of the event relative to the end of the wire. This gives a good measure of the position of the event along the wire.

The pulse height information is used for background reduction by excluding events which have pulse heights which do not correspond to the X-ray energies of interest. The diffracted X-rays are typically focused on a fairly small portion of the detector. The imaging capabilities of the detector can then be used to identify and eliminate events which fall far outside the predicted focus region on the detector[7].

The data used here were analyzed by T. Markert[14] in 1982–3 and do not represent the current state of the art in FPCS data reduction. The FPCS Data Archive Project[12] will provide a complete data set from the FPCS with consistent state of the art data reduction. Unfortunately, data from the archive project were not available in time for use in this paper.

The data provided by Markert[14] for use here are the integrated fluxes for each line group (e.g. Si XIII triplet) normalized to the HRI image of Tycho. The best estimates of the FPCS efficiency have changed markedly since these data were reduced[17]. We have corrected the data for the new efficiency estimates, averaged multiple observations, and corrected for the interstellar Hydrogen column density (from 21 cm radio data), $N_H = 2.5 \times 10^{21}$ cm^{-2}[10].

3 The Numerical Model

The numerical model to which we compare the observed spectra is the one described by W. Brinkmann, *et al.* in [2]. The model follows the hydrodynamic evolution of the remnant using a 1–D Lagrangian hydrocode which has been modified to include the ionization calculations. They assume that temperature equilibrium between the electrons and the ions is established by non-linear plasma processes such as those postulated by McKee[13]. This assumption is a radical departure from the assumption of other models (e.g. Itoh, *et al.*[11]) that the electrons are heated by Coulomb interactions alone, resulting in an electron temperature that is much lower than the ion temperature.

Type I supernovae are believed to be the result of the carbon deflagration of a white dwarf. The W7 model of Nomoto, *et al.*[16] models such an explosion and is therefore used to determine the initial conditions for the Brinkmann model. Brinkmann, *et al.* further assume that the remnant expands into a homogeneous interstellar medium with solar abundances. With these assumptions, the entire evolution of the model is dependent only on the number density of the interstellar material, n_0.

Brinkmann, *et al.* found that the model described above could not match the observed X-ray emission line spectrum of EXOSAT GSPC observations of Tycho unless they assumed $n_0 > 2$ cm^{-3} in which case the total X-ray emissivity of the model exceeded the observed value. They overcome these difficulties by introducing partial mixing of the ejecta with the interstellar medium in the outer regions of the remnant.

With the partial mixing in place, they obtain an approximate fit for the emission spectrum as observed by the EXOSAT GSPC. The primary difference between the model and observed spectra is that calculated Fe and S complex centroids are systematically shifted to higher energies. This indicates that Fe and S are somewhat over-ionized in this model. They attribute the over-ionization to technical uncertainties in the numerical model, different physical processes in the plasma(e.g. non-maxwellian electrons), and/or uncertainties in the actual origin and structure of the remnant.

The data used here to study the model are the results of more recent calculations in which the model has been adjusted for a best fit to recent *Ginga* observations of Tycho at energies greater than 8 KeV[3].

4 Plasma Diagnostics

A SNR is a hot diffuse plasma in which the matter is so diffuse that the collisional excitation timescale is many orders of magnitude longer than the timescale for radiative decay. In such a plasma, decays proceed at a much faster rate than excitation and almost every excited ion has time to decay radiatively before it is disturbed by a collision. This means that every ion is nearly always in its ground state and that when excited, it usually decays by photon emission. Plasmas of this kind are referred to as *coronal* plasmas[7].

Coronal plasmas are typically highly non-equilibrium systems. In equilibrium, one would expect the distribution of excited states of a particular ion to be given by a Maxwell-Boltzmann distribution but in a coronal plasma, most of the ions are in the ground state. Furthermore, the radiation from an equilibrium plasma would be that of a black-body but a coronal plasma emits a continuum of bremsstrahlung plus discrete lines. The plasma is optically thin to its own radiation so the major excitation mechanism is collisional excitation.

The ions in a SNR are heated by the shock and then transfer some of their energy to the electrons. The parameter that defines the timescale for the transfer of energy to the electrons is $\tau = n_e t$. If the sole mechanism for this transfer is Coulomb interactions, one would expect a characteristic time for equilibration of electron temperature to ion temperature of $\tau \sim 10^5$ yr cm^{-3}. Given typical ages and electron densities for SNRs it is clear that the electrons and ions have not reached thermal equilibrium. In contrast, the electron population can reach thermal equilibrium with itself in a short time: roughly $10 n_e^{-1}$ yr. Since this time is quite short relative to the age of known SNRs, we assume in our modeling that the velocity distribution of the electrons is Maxwellian.

The method used here to calculate the expected flux from an isothermal plasma of cosmic abundances follows that used by Mewe and Gronenschild[15]. The ionization structure for each element is calculated by solving a set of coupled differential equations (one for each ionization stage) for each element of interest. With the substitution of the ionization time, τ, the ionization structure becomes a function of T_e and τ. The ion abundances are then plugged directly into the equations for line emissivity resulting in a determination of the expected relative fluxes. Here, we use the measured flux ratios of selected transitions to determine a region of T–τ parameter space that is consistent with the observations.

5 Results

The plasma diagnostics described below are applied for line ratios calculated from our *Einstein* FPCS data[14]. Table [1] shows the exposure times, energy ranges,

Observation Name	Energy Range (eV)	Number of Observations	Total Exposure (ksec)	ISM Corrected Luminosity ($\times 10^{43}$ photons sec^{-1})
Si XIII	1830–1890	7	139.0	2.22 ± 0.24
Si XIV	1960–2040	1	6.3	1.64 ± 0.99
Fe XVII	810–850	3	17.2	1.39 ± 0.33
Fe XVII	1090–1140	1	9.2	0.70 ± 0.23

Table 1: Data from *Einstein* observations of Tycho's SNR

normalized ISM corrected luminosities for the observations we use.

5.1 Fe XVII: 820eV / 1120eV

The first diagnostic we consider is the ratio of the fluxes of the Fe XVII lines near 820eV with the lines near 1120eV. In the 820eV group we include two Fe XVII lines, their satellites, and some contamination by O VIII Ly γ. The 1120eV group includes three Fe XVII lines, their satellites, and some (very) weak Ni lines. Table [2] shows the photon flux ratios for both the *Einstein* data and the Brinkmann, *et al.* model. The given errors on the *Einstein* data are for the 90% confidence level.

Source	Flux Ratio
Einstein observations	$1.99 \pm^{1.67}_{0.85}$
Brinkmann, *et al.* model	0.2206

Table 2: Fe XVII 820eV / 1120eV flux ratios.

Calculations based on Mewe, *et al.*[15] indicate that the observed flux ratio corresponds to an temperature > $10^{7.1}$K. However, at these temperatures one would expect very little, if any Fe XVII to be present. The model flux ratio corresponds to an even higher temperature than the observed ratio and seems all the more implausible. Mewe, *et al.* note in their paper that in order to obtain agreement with observed solar spectra[6] they must multiply their calculated excitation parameters for the 820eV transitions by a factor of 1.5 and the oscillator strengths for the 1120eV transitions by factors in the range 2–5. It is clear that the basic atomic physics in this case is not well understood. We find that the model is very over-ionized relative to the remnant and suspect that there may be some fundamental problem with the atomic physics used in the model.

5.2 Fe XVII(820eV) / Si XIII

Next, we compare the Fe XVII 820eV lines to the Si XIII triplet at 1840eV. Table [3] shows the flux ratios for this diagnostic. If we assume solar abundances, the observed

Source	Flux Ratio
Einstein observations	$0.63 \pm^{0.24}_{0.20}$
Brinkmann, *et al.* model	0.0991

Table 3: Fe XVII (820eV) / Si XIII flux ratios.

ratio determines a rather small region of T–τ space as shown in Figure [2]. Also shown on the same plot is the contour determined from the model. The model contour is

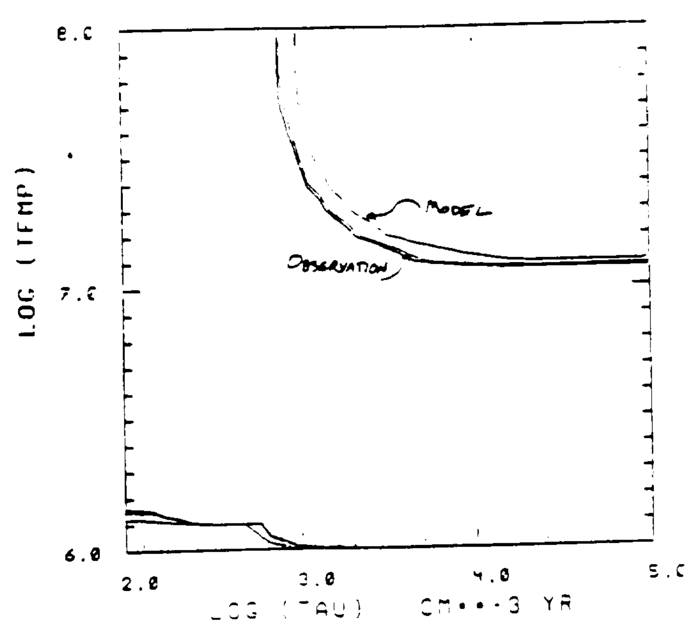

Figure 2: T–τ plot for the Fe XVII (820eV) / Si XIII diagnostic.

close but falls outside the 90% confidence region. We are somewhat uncertain about the accuracy of this diagnostic because of the above mentioned uncertainties in the atomic physics on which it is based.

Other investigators[1] find Tycho to be substantially enriched in Si relative to solar abundances. Our observations do not support this conclusion but it is clear that we need a better understanding of the atomic physics in order to understand this diagnostic.

5.3 Si XIV / Si XIII

The Si XIV Ly α/ Si XIII triplet flux ratios are shown in Table [4]. Again, the model

Source	Flux Ratio
Einstein observations	$0.74 \pm^{0.59}_{0.48}$
Brinkmann, *et al.* model	1.778

Table 4: Si XVI / Si XIII flux ratios.

ratio falls outside our 90% confidence region but maps to a nearby contour in T–τ space. Figure [3] shows the T–τ plot for this diagnostic.

6 Conclusions

Since we know the age of the remnant at the time of observation (~409 years) we can find a reasonable range for τ by looking at the n_e determined by other observers[18]. This yields estimates for the electron number density in the range

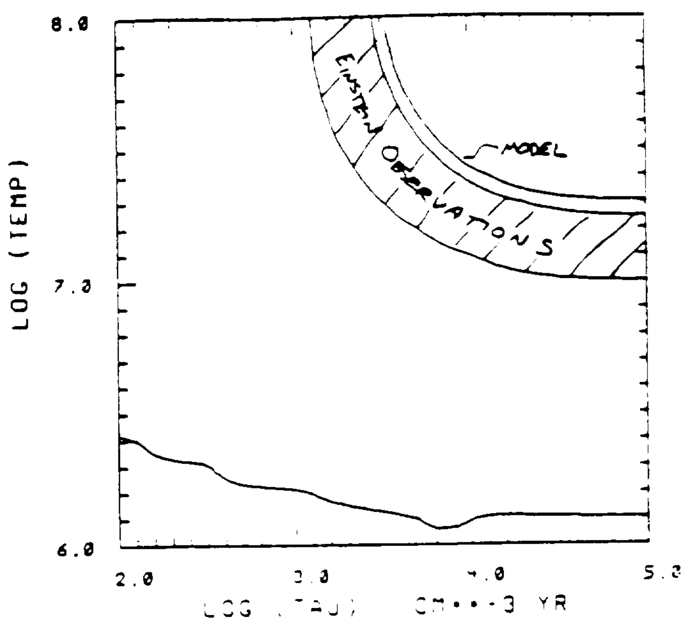

Figure 3: T–τ plot for the Si XIV / Si XIII diagnostic.

$n_e = 0.61$–$4.6\ \mathrm{cm}^{-3}$. The corresponding $\log(\tau) = 2.4$–$3.3\ \mathrm{cm}^{-3}$ years. From Figures [2] and [3] we see that our diagnostics demonstrate that this range in τ corresponds to $\log(T) \geq 7.5$. This temperature is at the high end of the range temperatures reported by other investigators[1, 9, 14, 18] which are in the range $\log(T) = 6.7$–7.3.

Our examination of the model by Brinkmann, *et al.* is (we believe) the first careful examination of the low energy X-ray emission line ratios it predicts. We find evidence that there are some fundamental problems with the atomic physics used in this model.

6.1 Acknowledgments

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